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Lunar Contour Crafting – A Novel Technique for ISRU-Based Habitat Development

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Habitat Structures - Introduction

- Habitat Structures at MSFC is one element of the In-Situ Fabrication and Repair (ISFR) Program
  - ISFR develops technologies for fabrication, repair and recycling of tools, parts, and habitats/structures using in-situ resources
  - ISRU-based habitat structures are considered Class III (iaw NASA 1997 Habitat Development Roadmap (Cohen & Kennedy)) and apply primarily to Spirals 3 (Moon) and 5 (Mars)

- Habitat Structures Purpose:
  - Develop Lunar and/or Martian habitat structures for manned missions that maximize the use of in-situ resources to address the following agency topics:
    - Bioastronautics Critical Path Roadmap (BCPR, Rev. E)) risks
      - Risks 31-35 (Radiation Health) , 43-44 (ALS) & 49 (SHFE)
    - Strategic Technical Challenges defined in H&RT Formulation Plan, v. 3.0
      - Margins & Redundancy - Reusability
      - Modularity - Autonomy
      - Robotic Networks - Affordable Logistics Pre-positioning
      - Space Resource Utilization

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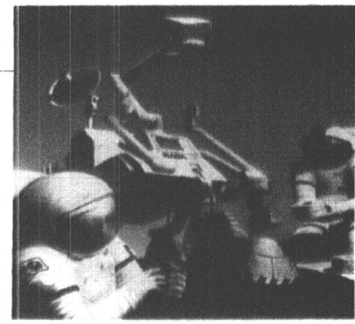
Habitat Structures - Introduction

- Habitat Structures – Top-Level Requirements
  - Support a pressurized (shirtsleeve) environment for the crew
  - Protect the crew from a worst case radiation (GCR & SPE) exposure
  - Protect the crew from micrometeorites and exhaust plumes
  - Initially, be able to be fabricated in advance of a manned crew so as to provide immediate protection (semi-autonomous construction)
  - Early, achievable, and visible milestones and successes are required
  - Development should be evolutionary and scalable
  - Present a psychologically/ergonomically compatible living environment for the crew
  - Maximize utilization of in situ resources

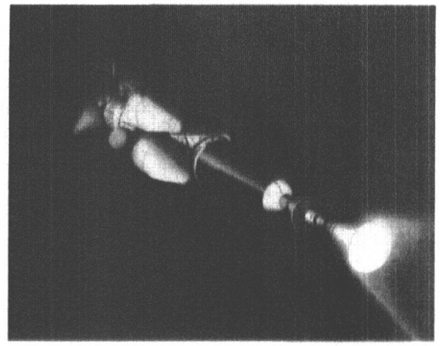
Habitat Structures - Interfaces

Crew



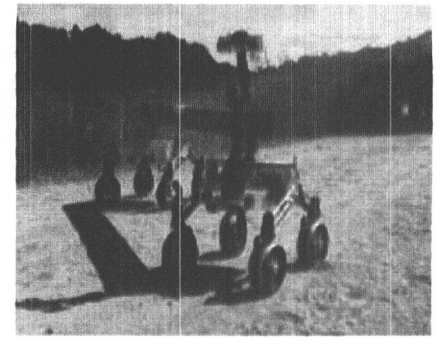
Radiation Shielding
Shelter and Storage
Hermetic Atmospheric Environment
Assembly, maintenance and repair support
Micro-meteorite hit protection
Exhaust Plume protection

Vehicle



-Transportation of equipment upmass/upvolume
-Temporary Shelter
-In-flight habitat materials development

Robotics

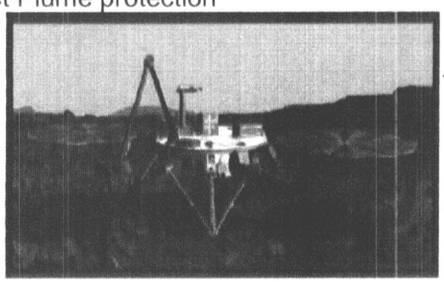


Semi-autonomous Construction
Scouting: exploration of resources
Materials Sampling
Information Gathering: locations, scheduling, prioritization

ISFR

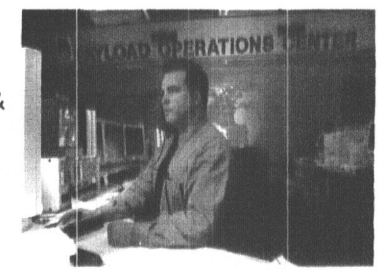
- Fabrication
- Repair
- NDE/NDI/NDT
- Recycling
- Habitat Structures

ISRU



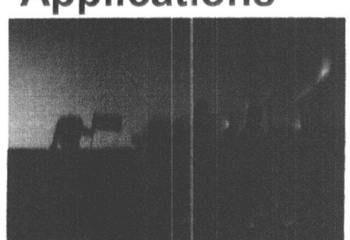
Feedstock for fabrication and repair materials
Regolith by-products (glass, metals, thin films, etc.

Ground Ops



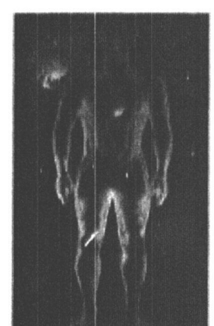
Operations Management & Decision Support
Exploration Planning
In-Situ feedback analysis

Spiral "N" Applications



-Technology Development for Spiral "N" Applications
-Technology Maturation/Extension

ECLSS



ALS
EVA
Power
Cooling
Heating

Logistics

Provisions
Parts and Supplies

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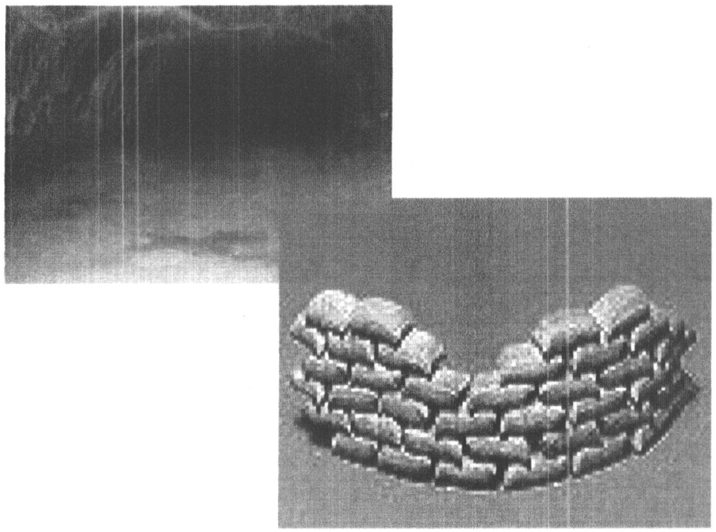
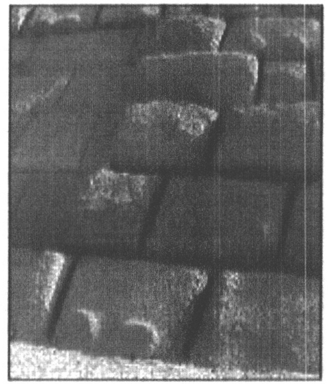
Habitat Structures – Construction Products

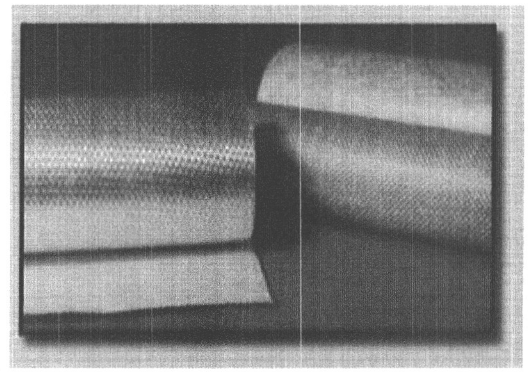
Raw Regolith

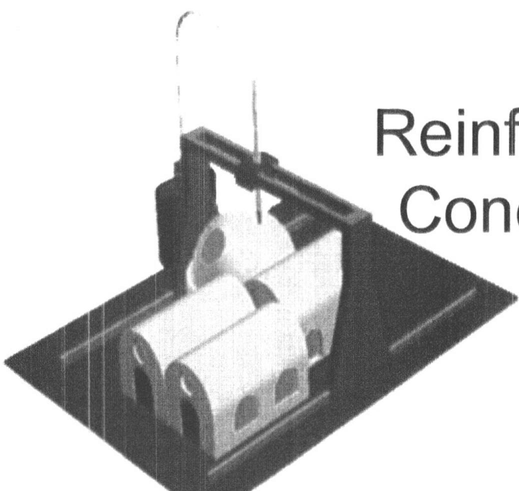




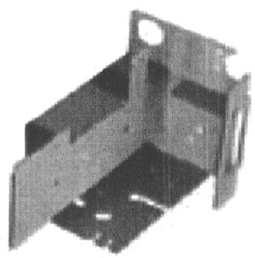
Blocks

Glass Products



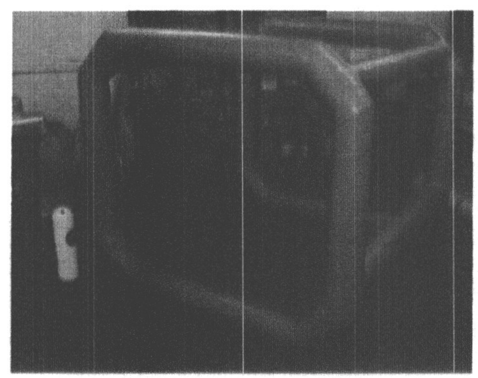


Reinforced Concrete



Deployable Metal Structures

Thin Films/ Inflatables



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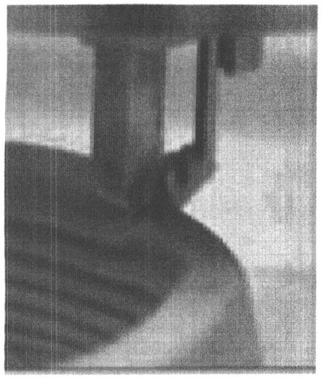
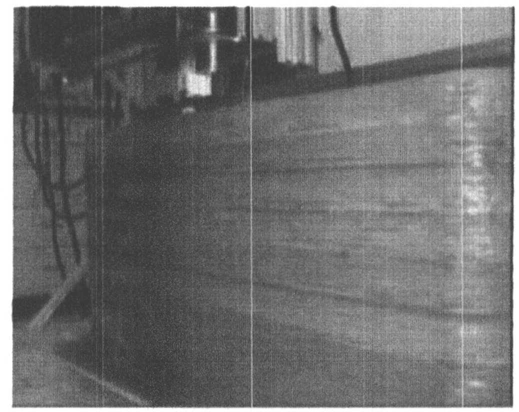
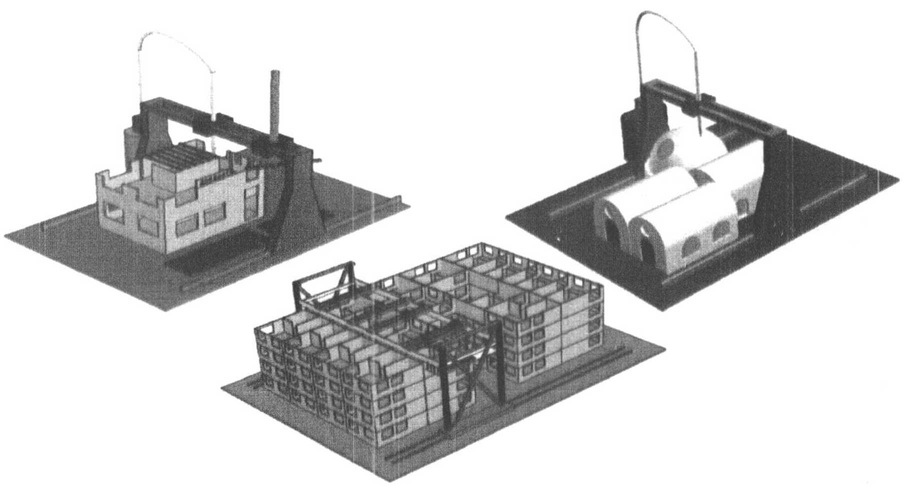
What is Contour Crafting?



- Developed at USC, CC is the application of layered fabrication (also known as solid freeform fabrication or rapid prototyping to construction, particularly with concrete
- Computer-controlled, CC delivers superior surface finish and accurate planar or complex geometries
- Terrestrial applications for low income and Army field housing



- Vertical slope can be changed (domed structures)
- Utilities and/or radiation-shielding materials can be incorporated
- System has been demonstrated at a subscale level, utilizing batch processing



- Can envision large gantry system or multiple robots constructing large-scale terrestrial facilities
- High degree of automation lends CC to other planetary applications

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Elements of Lunar Contour Crafting

-Process Development
  - USC, MSFC

- Robotic Operations for Lunar Construction
  - JPL, USC, MSFC

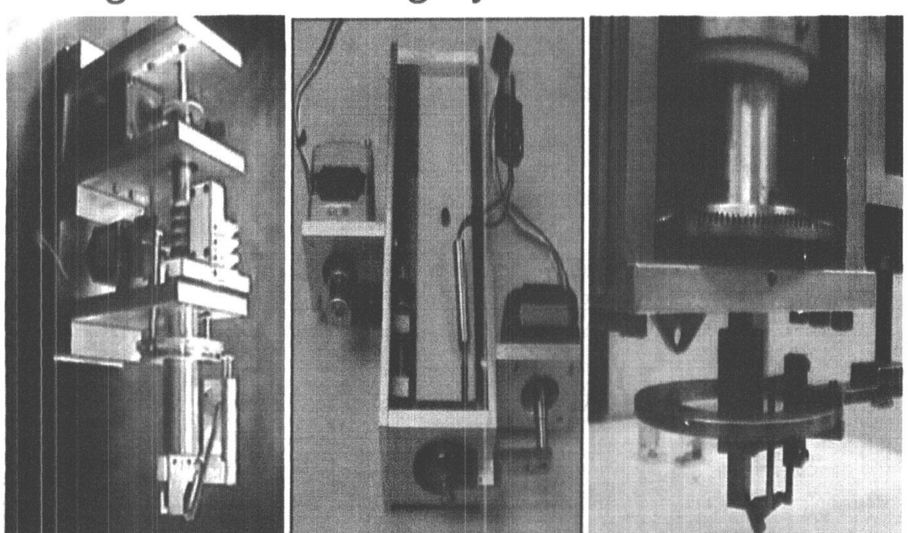
- Concrete Development
  - UAH, MSFC

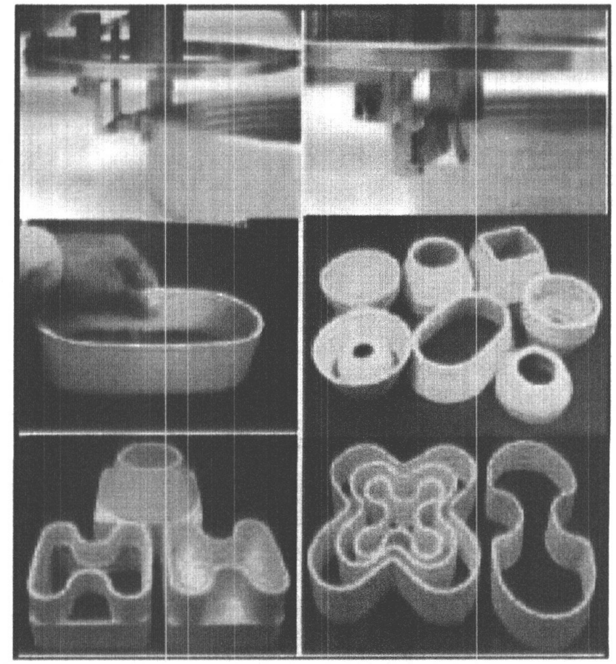
- Glass Reinforcement Development
  - MSFC

- Integrated Testing
  - MSFC, USC, JPL, UAH

Process Development

- Refinement of nozzle, top and side trowel materials and configuration
- Refinement of ability to generate non-orthogonal surfaces (side trowel orientation control
- Incorporation of integrated flow start/stop capability
- Variable-position nozzle for tight inside corners
- Integrated cleaning system





- Three-dimensional head movement, 6 DOF delivery
- Continuous processing vs batch processing
- Incorporation of utilities such as:
  - -Electrical
  - -Plumbing
  - -Radiation shielding materials

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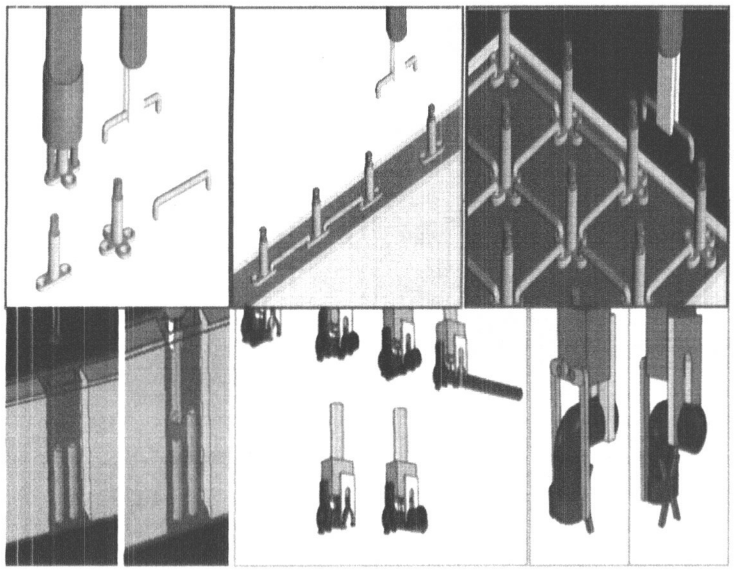
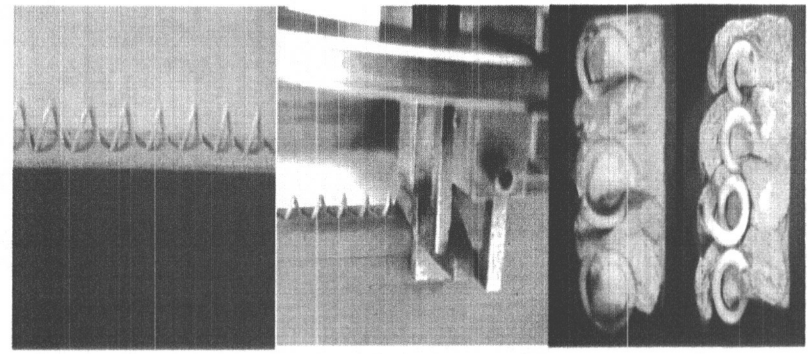
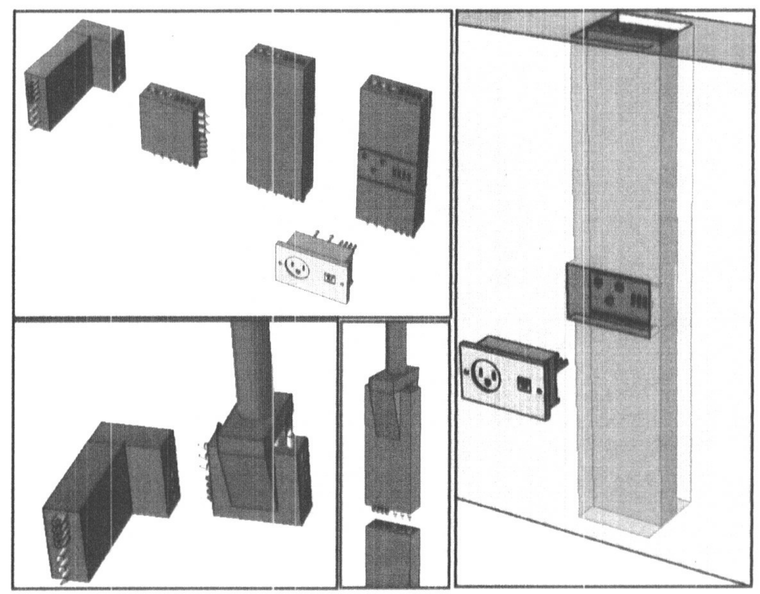
Infrastructure Support







- Structural reinforcement can be mixed into concrete (glass fibers) or installed during fabrication
- Electrical and plumbing components can be integrated into wall (better on ID for surface applications)
- Radiation shielding components can be integrated into wall, or on either surface

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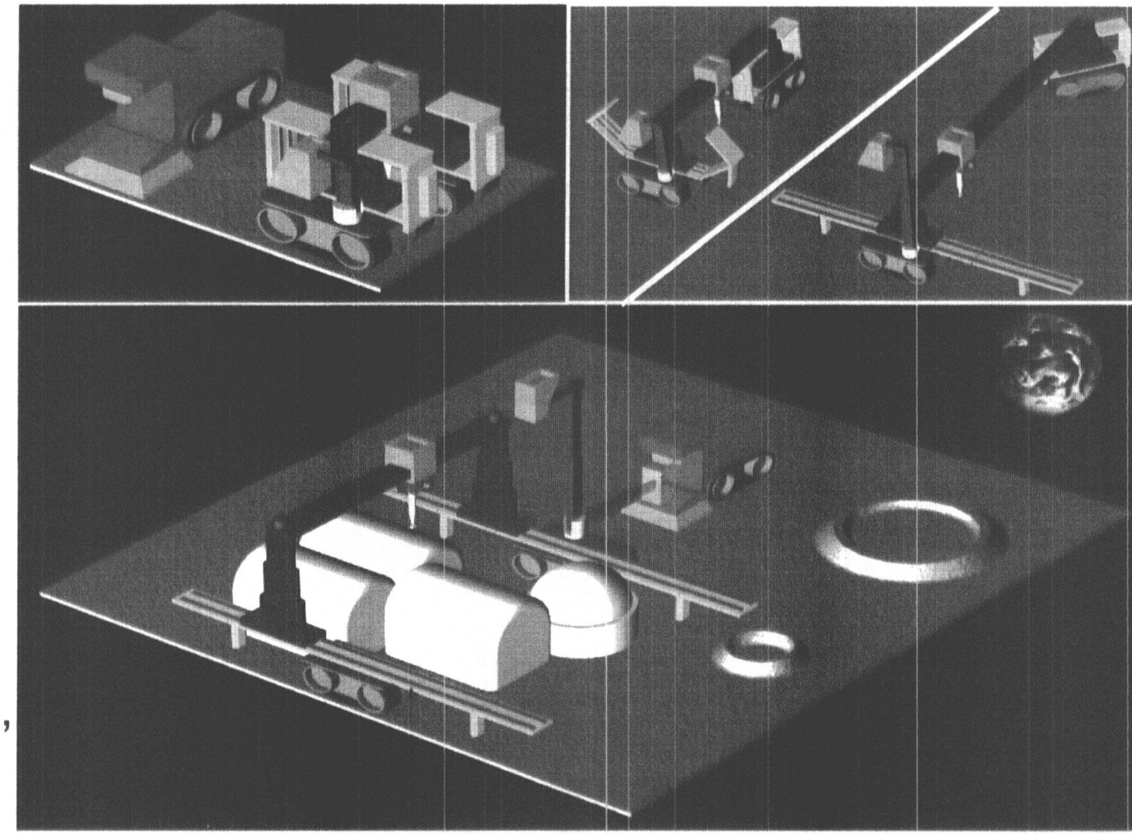
Robotic Operations for Lunar Construction



- Robotic configurations include gantry system and/or multiple, independently controlled robots
- System can be designed for mobility in the event that crews must change habitat locations
- Telescoping and/or foldable beams can be used for main cross beam, guide rails, and vertical supports
- Proximity controls can be incorporated for later structures development with a manned presence
- Completely autonomous control on the Moon must be demonstrated in order to be a successful tech demo for future Mars applications (time delay)

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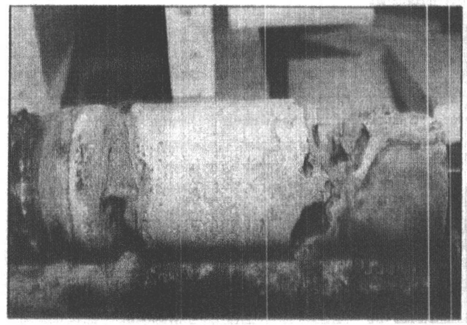
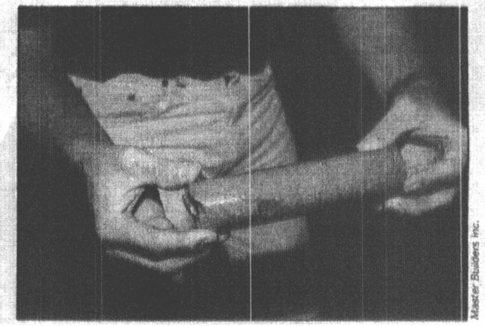
Concrete Development

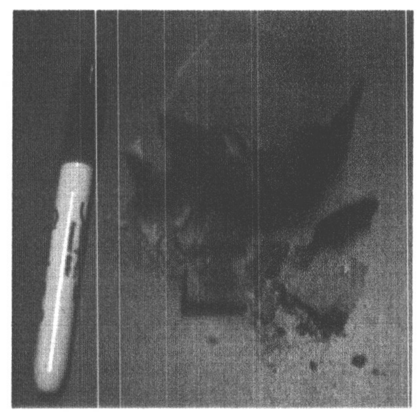




- 1994 STS GAS Can experiment prepared traditional concrete samples with mixed results
- Techniques include:
    - Wet-mix method
    - Dry-mix/Steam Injection (DMSI)
    - Waterless Regolith Mix (WRM)

	Compressive Strength, mPa	Tensile Strength, mPa
LRS/Sulfur Mix	62	7.4
LRS/Portland Cement	35	2.5

- ISFR effort focused on development of "waterless" concrete
-Sulfur-based concrete feasible:
    - Sulfur readily available
    - Good mechanical properties
    - Rapid setting
    - High chemical resistance
    - Low water permeability



- Constraints include:
    - Volume change/softening of S at 96°C
    - Combination of low temperature and low pressure on S sublimation
        - Effect of thermal cycles on strength
- Current research includes:
    - Additions of Dicyclopentadiene to improve strength
    - Effects of glass fiber additions on strength

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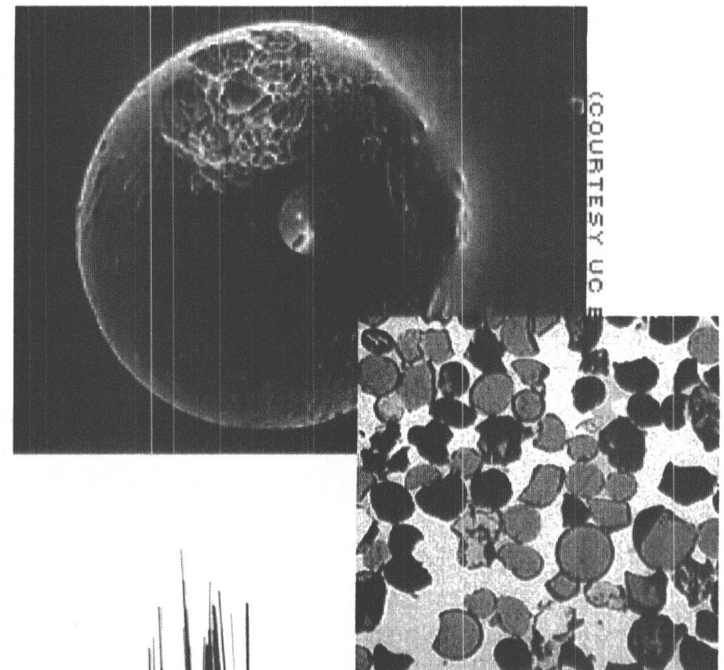
Glass Reinforcement Development

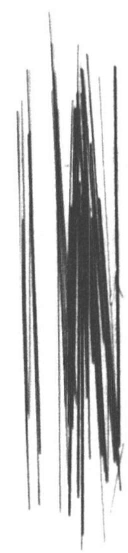
- Lunar regolith is comprised of up to 80% glassy materials, depending on regolith "maturity"

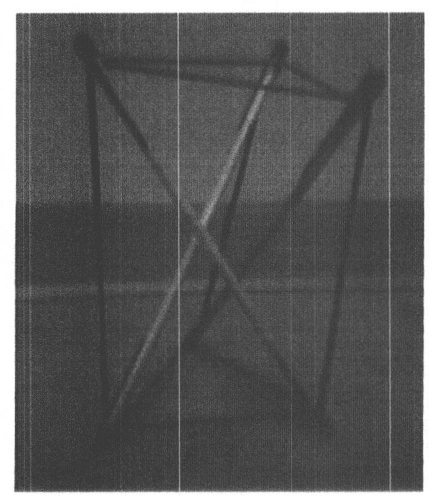
- Mechanical properties of lunar-derived glass are expected to be significantly higher than terrestrial glass, based on lack of water during glass formation

- Current work includes:
  - -Use of solar-powered furnace to melt LRS, fabricate glass beads and/or fibers
  - -Evaluation of additives required to tune optical properties of LRS-derived glass

- Applications for glass products include:
  - electrical and thermal insulation
  - braided cables
  - reinforcement in structural materials
  - struts
  - compression members in tensegrity structures
  - optical elements







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Test Status

- Currently modifying prototype hardware by:

  - Addition of limit switches

  - Addition of “home” or “stop” position

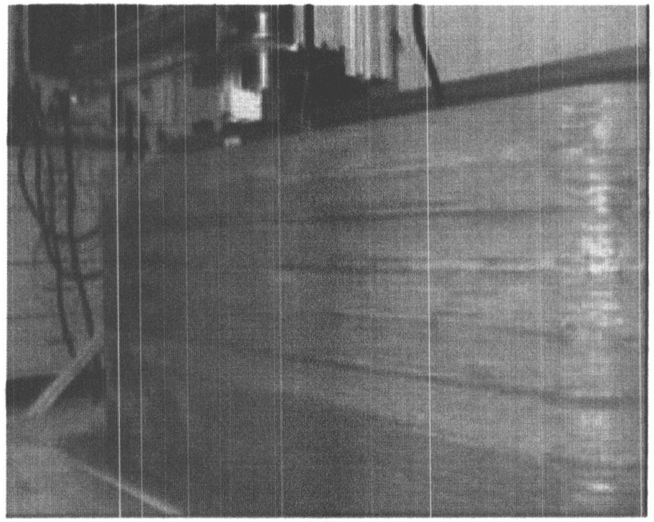
  - Addition of a third axis of motion to aid in development of more complex shapes

  - Software upgrades

  - Use of LRS-based concrete

  - Addition of capability for continuous processing for future operations

  - Addition of solenoid “shutter” and pressure relief for stop/start operations and air purging of system



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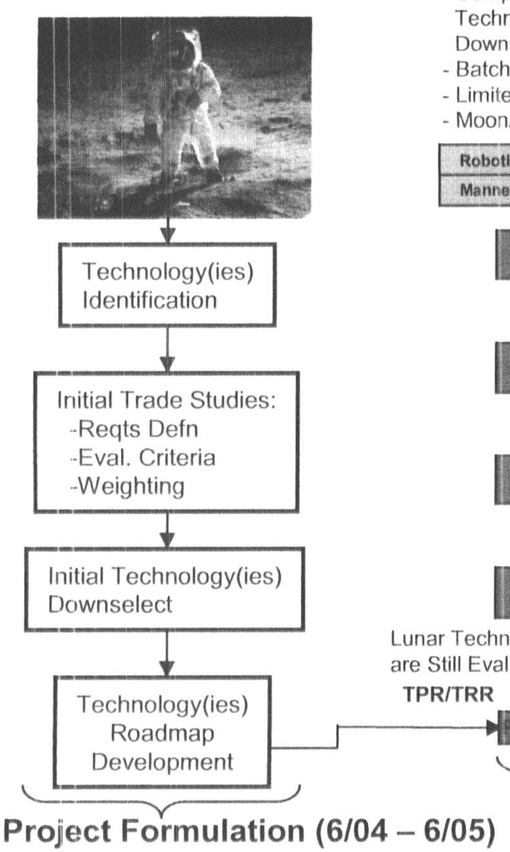
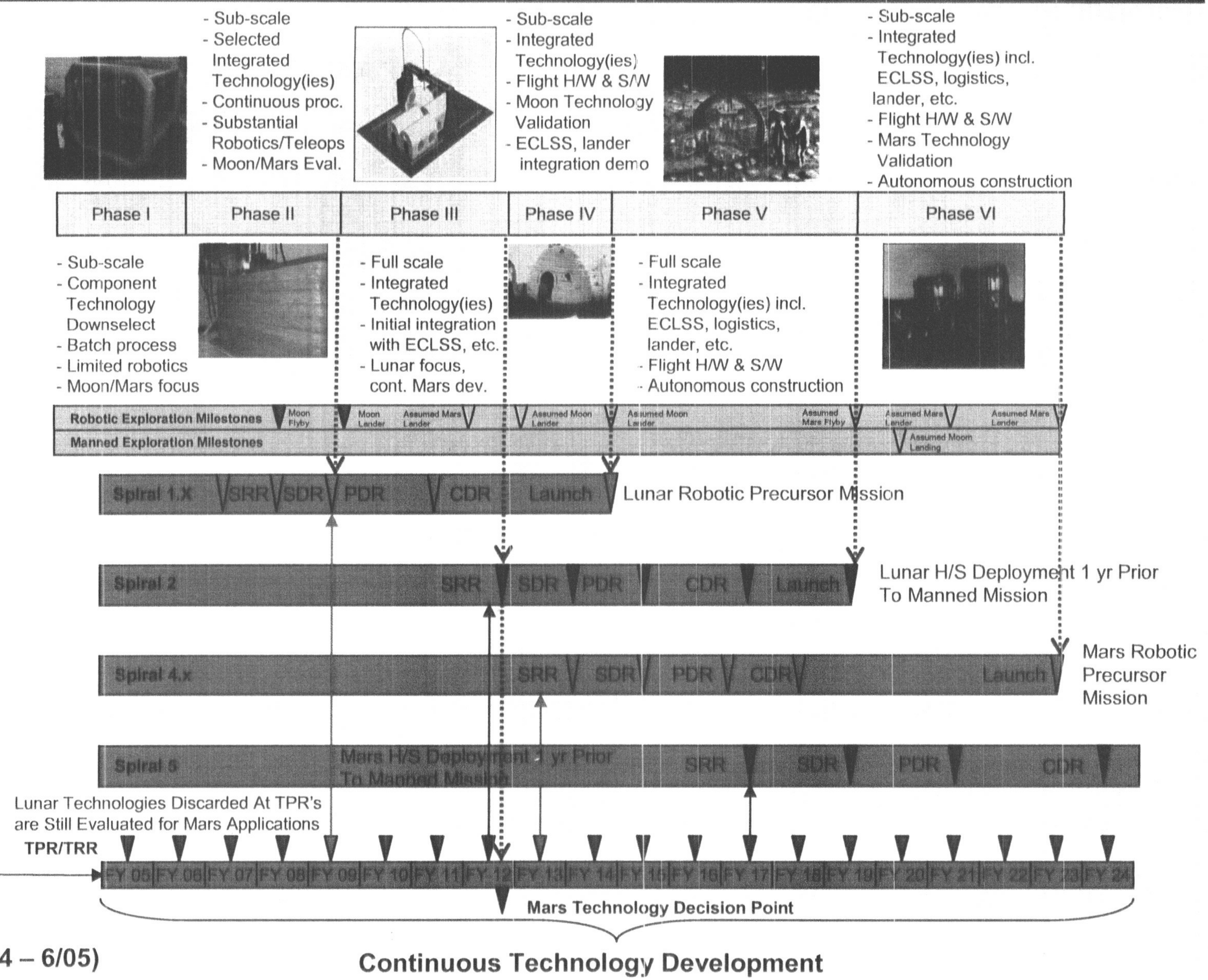
ISFR Habitat Structures Capability Evolution Roadmap

Current SOA:
-Lots of 10-20 yr old Studies
-Limited experience w/Lunar-based concrete, blocks or glass
-Few applications of space-based inflatables





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Habitat Structures – Fabrication Challenges

- Lunar soil (regolith) is well characterized, but from limited locations (Apollo, Luna, Surveyor)
- Probable South Pole location of Moon base is essentially uncharacterized
- Lack of large quantities of high quality Lunar Regolith Simulant (LRS)
- Design must support high tensile loads due to pressurized environment – habitat is a pressure vessel!
- Pre-manned mission construction requires complex robotics and teleoperations
- Integration of utilities and radiation shielding materials
- Configuration-specific technical challenges, for example:
  - Reinforced Concrete
    - Extruded in place vs pre-cast, pre-stressed
    - Steel vs glass rod reinforcement
    - Water-based vs waterless concrete
    - Hermeticity

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Near-Term Development Activities

- Lunar regolith simulant characterization
  - JSC-1 (NASA/JSC)
  - JPT-1890 (Jensan Scientific)
- Concrete development/testing
  - Sulfur & LRS-based concrete testing in work
    - Significant improvements in tensile & compressive strength over Portland cement-based concrete
  - Effects of simulant on materials properties to be evaluated
  - Testing with prototype Contour Crafting system in MDL
- Compacted block development/testing
  - Binderless compacted JSC-1 LRS block did not hold together
  - Evaluating potential binders
- Radiation shielding modeling/testing of candidate configurations
- Evaluation of all technologies with respect to acceptance criteria (being defined), including TRL and RD^3 assessment
- Definition of technology exit criteria

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